Direct imaging of subtle, zero throw vertical faulting – a 3D real data example

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Summary:

Conventional pre-stack depth migration (PSDM) is capable of imaging vertical boundaries provided the geology has strong vertical velocity heterogeneity and the seismic is recorded with a very large surface aperture. This paper describes a Kirchhoff implementation of Duplex Wave Migration (DWM) that removes these limitations and we illustrate how DWM can provide an entirely new methodology for using seismic data to directly image and delineate subtle, zero throw fault compartmentalization within the reservoir. A 3D data set from the Western Canadian Basin (WCB) will be used to illustrate the ability of DWM to image a well known normal fault, a vertical dyke that is detectable using an aeromagnetic survey but invisible on 3D seismic data and additional parallel and orthogonal vertical faulting that is invisible to both aeromagnetic surveys and 3D seismic surveys. The new knowledge about these vertical faults is used to explain unusual well results in the area and to indicate alternative sources for the hydrocarbon flow.

Introduction:

The imaging of vertical boundaries has become extremely important for solving a whole host of exploration and production challenges. These include salt wall imaging, zero or near zero throw faults within the reservoir (fault compartmentalization), zones of fracturing, locating diagenetic reservoirs formed by basinal hydrothermal fluid flow along vertical faults (Hickman and Kent, 2005), identification of bypassed reserves (enhanced recovery) and the delineation of the edge boundaries of oil (or gas) to water interfaces.

Marmalyevskyy et al. (2005) presented a Kirchhoff method for DWM that successfully imaged vertical boundaries from salt walls and subtle zero throw faults within the sedimentary section while at the same time automatically attenuating all energy other than the duplex wave energy (DWE). DWE is defined as a seismic event that has undergone two bounces. In this paper we will present an example of 3D DWM on a 3D data set from the WCB to identify otherwise seismically invisible vertical boundaries.

Method:

We have developed a Kirchhoff depth migration that is based on the Green's function using the kinematics of DWE. A primary event (that must be deeper than the vertical boundaries we wish to image) is defined in depth by the user. It is assumed that a conventional PSDM has been run prior to running DWM, therefore we use the depth model generated from that process as a starting point. The depth model can be either isotropic or TTI anisotropic. The TTI travel time calculations are generated using an eikonal solver as described by Roganov (2006).

Figure 1 illustrates where DWM fits within the processing and interpretation workflow. DWM is a new type of depth migration that is run after conventional depth migration has been used to define dips from 0 to 60 or 70 degrees. DWM uses exactly the same input data and information, plus the location of a deeper mirror event, to provide critical vertical boundary information. This information about the vertical boundaries means that seismic data can now be used for more detailed reservoir development and for general enhanced oil recovery (EOR) purposes.

The DWM algorithm is designed to image the DWE that will arrive at a time greater than that of the primary base boundary. A beam tube construction eliminates the migration noise that would result from including the base boundary primary reflections in the migration summation. Tight control of the aperture is also key to suppression of artifacts from primary reflections. Each DWM run produces four separate and distinct views of the vertical boundaries based on two possible bounce orders – base boundary then vertical boundary or vice versa and traces input to the migration are either to the right of the shot or to the left of the shot.

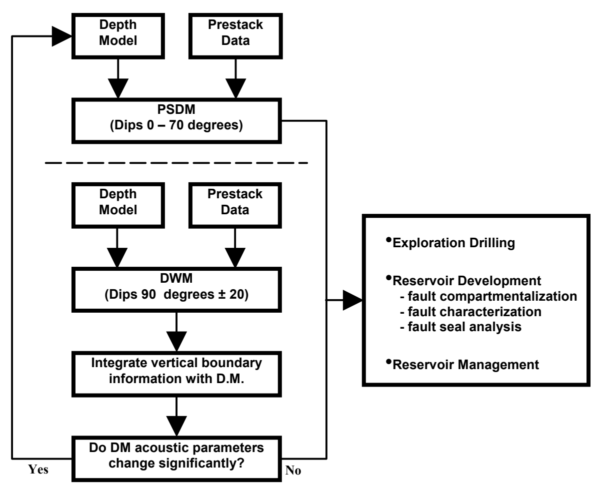

Figure 1: DWM fits after conventional PSDM – it adds vertical boundary information.

The four categories of observation systems are illustrated in the upper portion of figure 2(a). The HV and VH designate horizontal to vertical boundary ray paths and vertical to horizontal boundary ray paths respectively. The shot spread configurations illustrate imaging aperture to the right and left of the shot point.

The fact that we use a Kirchhoff implementation means that the data need not be regularly sampled in space. Also, the Kirchhoff implementation allows for efficient and targeted velocity analysis by generating a series of migrated DWM 3D view cubes. Since we have multiple views of the same vertical boundaries we can use the correspondence of lateral positioning as the criteria for correct velocities. This means we no longer need to rely on flatness of migration gathers as our only method for fine-tuning the velocity model. It is hoped that this new methodology and velocity correctness criteria will improve our ability to measure anisotropic parameters. Modern 3D visualization technology is used to integrate the additional information about vertical boundaries into the pre-existing PSDM depth model. If the changes in structure or velocities are significant then we may wish to rerun the PSDM.

Synthetic data example:

Figure 2(a) illustrates a simple box fold depth model that was used with a full wave forward modeling program to produce a 2D synthetic data set over this structure. Note that under the box fold there is no acoustic impedance contrast. This structure is common in the Canadian foothills thrust belt. The key problem associated with these features is defining the location of the vertical walls of the box folds. Figure 2(b) shows the results of conventional PSDM. The vertical walls are not imaged in 2(b)

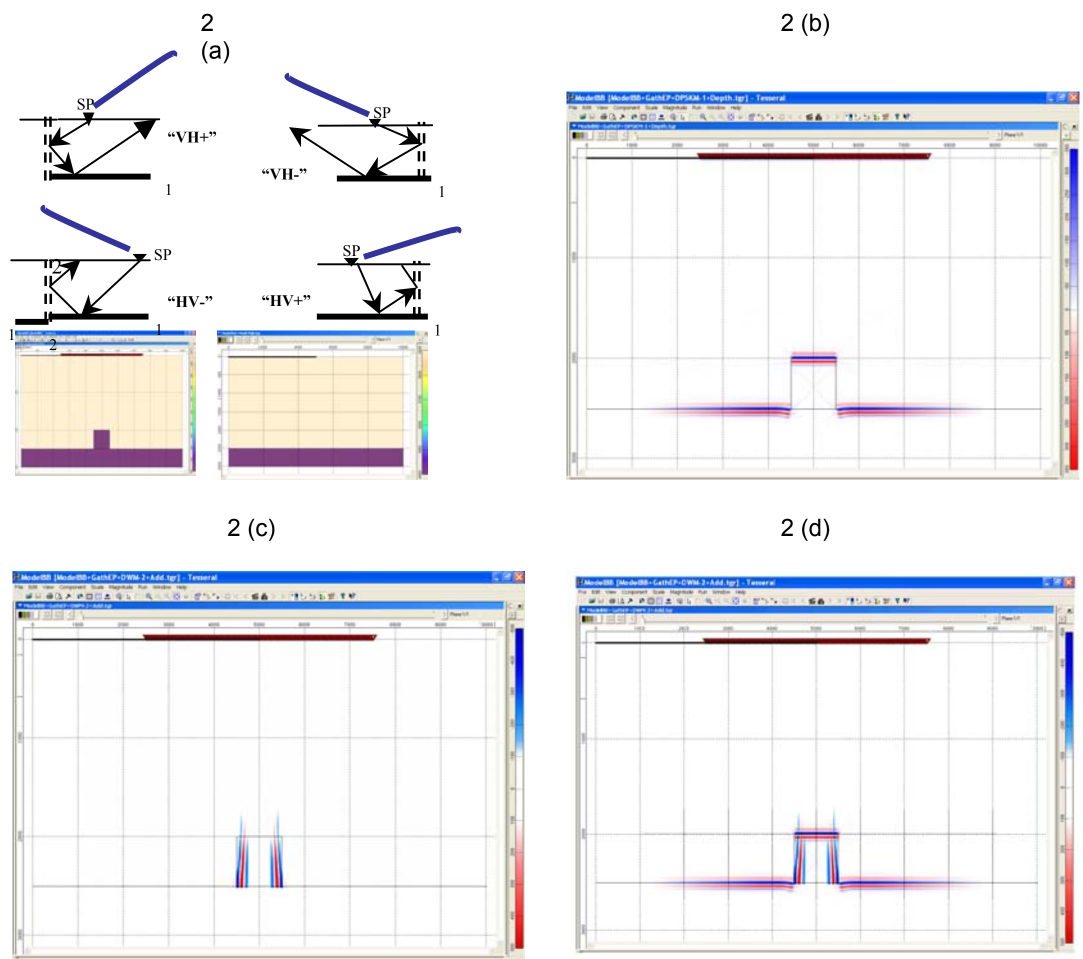

Figure 2: a) Full wave forward modeling of a box fold and four DWM observation categories. b) Conventional PSDM can not image vertical walls of box fold. c) DWM defines vertical edges of box fold. d) Conventional PSDM image plus DWM image.

because single bounce energy does not return to the surface after reflecting off of the vertical boundaries. However, two-bounce information does return and can be imaged by DWM as in figure 2(c). Note that the depth model that is used as input to the DWM (lower right in 2(a)) does not contain any information about where the box fold is located, or even that the box fold exists. Figure 2(d) illustrates how vertical boundary information from DWM can complete the structural image of this geologic feature.

Real 3D data example from the Western Canadian Basin:

It is well known that NW to SE trending lineaments, and a near orthogonal set of NE to SW trending lineaments exist throughout the WCB (K.S. MISRA et al., 1991). These vertical faults originate from block faulting in the Precambrian basement and they often have little or no vertical throw, therefore they are generally invisible to conventional seismic imaging. In some areas the faults have been intruded by igneous rocks that in some cases outcrop at the surface. A NW to SE linear dyke has been revealed by an aeromagnetic survey in the north half of the example 3D survey (figure 3(b)). The dyke is invisible on the coherency cube of the conventional PSDM product as is illustrated in figure 3(a).

This land 3D is about 25 square Km in area and is shot with an orthogonal shooting pattern. On the surface no evidence of an igneous dyke exists – it only became apparent after the aeromagnetic survey was done. About 40 Km to the NW of this 3D the dyke does outcrop at the surface and the igneous rock component is verified. As is shown in figure 3 (a) the conventional PSDM correctly identifies a well-known north-south trending normal fault. The displacement across this fault is about 40 meters and conventional seismic imaging techniques are capable of delineating this fault accurately. To do this we do not image the fault reflection directly but we infer the existence of the fault by measuring and highlighting the lack of coherency in the sedimentary beds from one side of the fault to the other.

DWM also images this normal fault as can be seen in figure 3(c). Note that the DWM also shows NW-SE trending linear events. Also identifiable are some NE-SW trending linear events. The interpretation of these vertical-faulting systems is shown in figure 3(d).

The red faults are believed to be associated with the igneous rock intrusions. Note that the orientation of these faults exactly aligns with the orientation of the aeromagnetic anomaly in figure 3(b). The blue faults are parallel faulting systems that are known to exist throughout the WCB. Also, the yellow faults are interpreted as a set of orthogonal faults.

The play in this area is a thin regional sand. The wells in figure 3(d) all produced gas shows, however all but one were not economic to develop. The well indicated with the red star produced gas for several years. This production history made no sense since the reservoir should have depleted very quickly since it is already known that the regional extent of the reservoir must be very small. The only explanation is that this gas is being fed from a deeper horizon through the vertical faulting system. Note that the one producing gas well exactly corresponds to an amplitude anomaly on the DWM image in figure 3(c) and it is at the junction of the orthogonal faulting systems. Deeper horizons also show the same faulting system.

Conclusions:

This 3D real data example from the WCB illustrates that vertical boundaries can be directly imaged using seismic data. This means that we can infer characteristics about the fault boundary by measuring the relative amplitude variations along the fault – direct imaging of reflections from the fault – not just observing lateral in-coherency.

It is hoped that this work will enable the identification of actual hydrocarbon migration pathways. The WCB is well drilled out to the shallow and intermediate depths. However DWM may be able to help us identify deep source reservoirs and thereby open up a revival of interest in this mature basin. DWM is capable of imaging deep vertical faulting – this is exactly the information that is missing from our conventional seismic processing products. Also, the surface aperture required to record duplex wave energy is very small – therefore, older data sets may increase in value dramatically.

3D DWM is a practical tool to delineate vertical boundaries that are invisible to conventional PSDM. Vertical faulting and fracturing is thought to be much more prevalent than we realize today. Diagenetic reservoirs that develop where hydrothermal flow is vertically directed were previously found only by accident but now we have a direct imaging technology to aid in a targeted search for these traps. Corrosive plumes above oil to water contacts can now be used to delineate reservoir boundaries. Perhaps the most significant potential of this technology is more effective EOR processes through accurate delineation of fault compartmentalization, fault characterization, fault seal analysis and the identification of bypassed hydrocarbons within the reservoir.

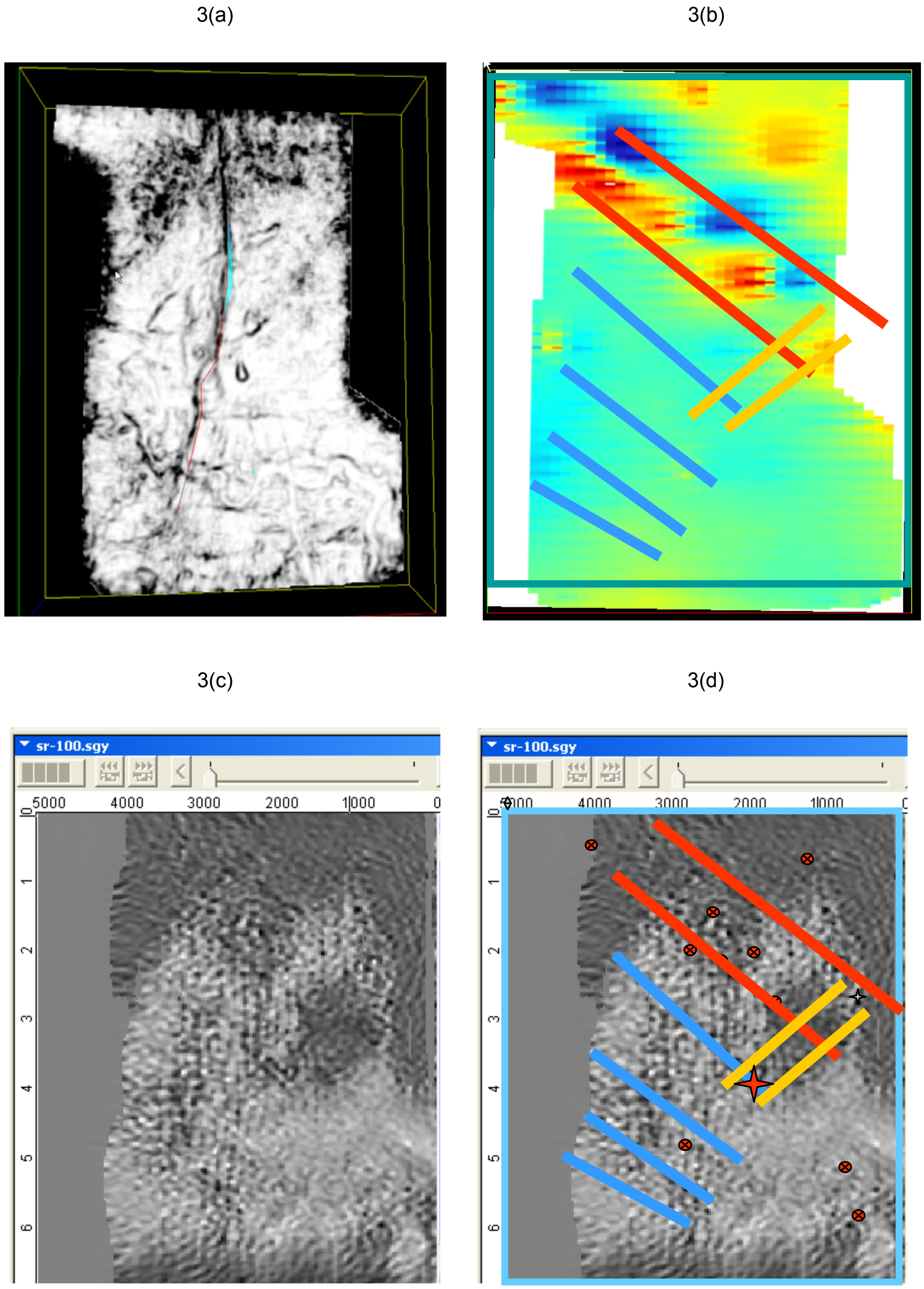

Figure 3: a) Depth slice of coherency cube computed from conventional PSDM. b) Aeromag survey with DWM interpreted faulting. c) Depth slice of 1 of 4 DWM cube views. d) Interpreted DWM depth slice – red indicates faults intruded with igneous rocks, blue and yellow indicate parallel and orthogonal faulting common in area.

EDITED REFERENCES

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